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Original Article

Topographic electroencephalogram changes associated with psychomotor vigilance task performance after sleep deprivation

Maurizio Gorgoni [a], Fabio Ferlazzo [a], Michele Ferrara [b], Fabio Moroni [c], Aurora D'Atri [a], Stefania Fanelli [a], Isabella Gizzi Torriglia [a], Giulia Lauri [a], Cristina Marzano [a], Paolo Maria Rossini [d,e], Luigi De Gennaro [a,e,*]

[a] Department of Psychology, "Sapienza" University of Rome, Rome, Italy
[b] Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy
[c] Department of Psychology, University of Bologna, Bologna, Italy
[d] Institute of Neurology, Catholic University of The Sacred Heart, Rome, Italy
[e] IRCCS San Raffaele Pisana, Rome, Italy

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ABSTRACT

Objectives: The psychomotor vigilance task (PVT) is a widely used method for the assessment of vigilance after sleep deprivation (SDEP). However, the neural basis of PVT performance during SDEP has not been fully understood. In particular, no studies have investigated the possible relation between EEG topographical changes after sleep loss and PVT performance. The aim of the present study is to assess the EEG topographic correlates of PVT performance after SDEP.
Methods: During 40 h of SDEP, 16 healthy male subjects were evaluated in four sessions performed at the same time (11:00 a.m. and 11:00 p.m.) of the first and second day with: (a) subjective sleepiness recordings by means of the Karolinska Sleepiness Scale (KSS); (b) EEG recordings (5 min eyes-open condition); and (c) PVT.
Results: SDEP induced a slowing of PVT reaction times (RTs), higher level of subjective sleepiness and an increase of delta, theta, alpha and beta 1 EEG activity. Only slowest PVT RTs were influenced by circadian factors, with longer RTs in the morning. Both fastest PVT RTs and KSS scores were positively correlated with post-SDEP changes in EEG theta activity, mainly in centro-posterior areas, but not with other EEG frequencies. KSS scores and PVT measures were also positively correlated.
Conclusions: These findings suggest that SDEP differently affects PVT variables, and that an increase in theta activity may be the principal EEG basis of the post-SDEP slowing of fastest PVT RTs. Similar neural mechanisms seem to underlie both performance deterioration to PVT and the increase of subjective sleepiness.

1. Introduction

Sleepiness is a widespread condition in modern society that represents a significant problem, being a major risk factor for accidents [1,2]. Sleep deprivation (SDEP) induces a severe deficit in alertness, as indicated by subjective and objective measures of sleepiness [3]. Sleep loss has degrading effects on simple task performance, indexed by reaction times (RTs), attention, and vigilance [4], as well as on complex task performance involving frontal lobes or executive functions [5].

The psychomotor vigilance task (PVT) [6] is a computerized simple cued RT task that provides a valid measure of sustained attention [7]. Due to its sensitivity to SDEP [8–10] and chronic sleep restriction [11], the PVT has become one of the most widely used methods to assess the effect of sleep loss on vigilance [7]. Nevertheless, only few studies have investigated the neural basis of PVT performance. From functional magnetic resonance imaging (fMRI) data recorded during the execution of the PVT [12], it has been observed that higher activity in a cortical sustain attention network and in the cortical and in subcortical motor regions was related to optimal PVT performance, whereas the slowest RTs, particularly during SDEP, were related to higher activation of the 'default

* Corresponding author at: Department of Psychology, University of Rome "Sapienza", Via dei Marsi, 78; 00185 Roma, Italy. Tel.: +39 06 49917647; fax: +39 06 49917508.
E-mail address: luigi.degennaro@uniroma1.it (L. De Gennaro).

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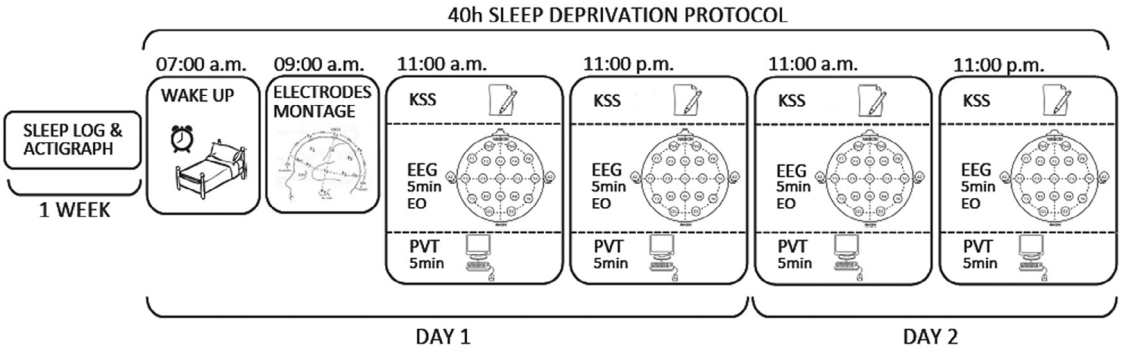

Fig. 1. Timeline of the experimental protocol. During the week preceding the beginning of the sleep deprivation (SDEP) period, subjects were monitored by actigraphic recording and sleep log. On the morning of the experiment subjects on average woke up at 07:00 (mean ± SE 6.54 ± 0.13 based on sleep log) and entered the laboratory at 09:00 for the electrode montage. Experimental procedure started at 11:00. Subjects were evaluated in four different sessions carried out at the same time (11:00 and 23:00) of the first and second day, each conducted in the following sequence: (a) subjective sleepiness recordings (Karolinska Sleepiness Scale); (b) electroencephalographic recordings (5 min eyes-open condition); (c) behavioral sleepiness recordings (5 min psychomotor vigilance task).

mode network', a brain network consisting of different frontal and posterior midline regions that are more active during resting wake than during cognitive task engagement [13]. However, these results are limited by the intrinsic difficulties of administering the PVT in the fMRI environment.

The electroencephalographic (EEG) correlates of the PVT after sleep loss are not well understood. An early study reports that the slowing of RTs after SDEP was associated with an increase in absolute EEG power (4–20 Hz), particularly in the left central cortex [14]. A positive correlation has been found after SDEP between PVT performance and frontal EEG power density in slow waves and theta bands [15]. More recently, decreased amplitude of the P1 component of event-related potentials (ERPs) and progressive reduction of theta and delta phase-locking index (PLI) have been observed over the course of SDEP by recording EEG hourly during PVT task performance [16]. However, Caldwell et al. [17] have found no correlation between EEG and PVT performance. To the best of our knowledge, however, the possible relation between topographic distribution of the EEG power after SDEP and performance on the PVT has never been investigated, despite the fact that there is a growing evidence of regional (cortical) differences in sleep and sleep need [18]. This may be relevant for understanding which areas and, presumably, which functions are affected by SDEP as assessed by the most-used task for measuring behavioral consequences of sleepiness. EEG measures have indeed indicated that the increase of low-frequency bands with time spent awake, considered as the main EEG marker of sleepiness, is particularly evident in fronto-central areas [19–21]. A significant increase in theta activity after sleep loss has also been observed in the occipital area [19]. Regarding the other EEG bands, both De Gennaro et al. [19] and Tinguely et al. [21] showed an increase in alpha and beta 1/sigma power, particularly in fronto-central areas (albeit secondary to the rise of theta power).

Hence, the main aim of the present work is to evaluate the EEG correlates of PVT performance during ~40 h of prolonged wakefulness. In particular, we have investigated the possible relation between performance at the PVT and the topographic distribution of delta, theta, alpha, beta 1 and beta 2 frequencies. Since the increase in low-frequency bands is considered the principal EEG marker of sleepiness, we hypothesized that SDEP would induce a generalized increase in EEG delta and theta waves, and that this phenomenon should be positively correlated with a slowing of RTs at PVT performance and an increase in subjective sleepiness.

2. Methods

2.1. Subjects

Sixteen healthy male volunteers took part in the experiment (mean age ± SE, 23.3 ± 0.64 years). All subjects reported themselves as right-handed and had no history of central or peripheral neurological impairments. In particular, exclusion criteria were: brain injury, alcohol abuse, diabetes, or drug addiction. Further requirements for inclusion were: normal sleep duration (habitual sleep time: 24:00–8:00 ± 1 h) and schedule, no daytime nap habits, no excessive daytime sleepiness, no other sleep, medical or psychiatric disorders, as assessed by a 1-week (7 ± 0.3 days) sleep log, administration of the Italian version of the Pittsburgh Sleep Quality Index (PSQI) [22], and a clinical interview. Participants were required to avoid napping; actigraphic recordings (AMI Mini motion logger) were collected for about 1 week (7 ± 0.3 days) before the beginning of the experimental procedure to control subjects' compliance.

All subjects gave their written informed consent. The study was approved by the Institutional Ethics Committee of the Department of Psychology of the University of Rome "Sapienza", and was conducted in accordance with the Declaration of Helsinki.

2.2. Procedure

2.2.1. Study design

Fig. 1 shows the timeline of the experimental protocol. On the morning of the experiment, participants on average woke up at 07:00 (6:54 ± 00:13 based on sleep log), and arrived at the laboratory at 09:00 for the electrode montage. Experimental procedure started at 11:00. Subjects were evaluated in four different sessions carried out at the same time (11:00 and 23:00) on the first and second day, with the aim to control for potential circadian effects. Each session was conducted in the following sequence: (a) subjective sleepiness recordings; (b) EEG recordings (5 min eyes-open condition); (c) PVT. During the experimental sessions, participants were seated on a comfortable chair in a soundproof, electrically shielded room.

When not involved in testing sessions, subjects were allowed to carry out their own preferred activities, such as reading, writing, listening to music, watching TV, or playing games, always under the direct supervision of at least one experimenter. Lying down, sleeping and vigorous physical activity were not permitted. Meals were provided to subjects at 08:30, 14:30 and 07:30. Non-scheduled light

snacks were permitted, whereas caffeinated beverages, chocolate, alcohol and medications that may influence sleepiness were not allowed during the deprivation protocol. Time information was available to subjects, and light exposure was not strictly controlled for (although the laboratory was constantly illuminated by four neon lamps, blinds only in part attenuated the light coming from the outside). The ~40 h schedule of SDEP ended at midnight on the second day.

2.2.2. Subjective sleepiness

Self-rated sleepiness was measured every 2 h (starting at 11:00 on the first day) by the Karolinska Sleepiness Scale (KSS) [23], a nine-point rating scale, ranging between "very alert" (1) and "very sleepy, fighting sleep" (9). According to the aims of this study and to the analyses on electrophysiological and behavioral measures, which were not collected every 2 h, only measures recorded in correspondence with the four experimental sessions (at 11:00 and 23:00 of first and second day) are reported.

2.2.3. Psychomotor Vigilance Task

A 5 min version of the PVT was administered as a behavioral measure of sleepiness. During the task, subjects were seated in front of a computer monitor showing a millisecond counter fixed at 0. The counter started to scroll at random intervals, and subjects had to stop it as quickly as possible by left-clicking on the computer mouse. Subjects were alerted by the experimenter if no response was given after 2000 ms, and those trials were excluded from the analysis. The task contained 60 trials.

2.2.4. Polygraphic recordings

An Esaote Biomedica VEGA 24 polygraph was used for EEG polygraphic recordings. Electroencephalographic signals were recorded from 19 sites using Ag/AgCl sintered ring electrodes mounted on an elastic cap (EasyCap GmbH, Herrsching, Germany). The 19 unipolar EEG derivations of the international 10–20 system (Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, P3, P4, Pz, T3, T4, T5, T6, O1, O2) were recorded from scalp electrodes with averaged earlobe reference (A1, A2). Horizontal eye movements were detected by recording electro-oculograms (EOGs) in order to monitor subject behavior online and reject, offline, trials with ocular artefacts. Electromyogram (EMG) was recorded by two submental electrodes. EEG, EOG and EMG signals were acquired at a sampling rate of 128 Hz. EEG signals were high-pass-filtered with a time constant of 0.3 s and low-pass-filtered at 30 Hz. Submental EMG was recorded with a time constant of 0.03 s. EOG signals were recorded with a time constant of 1 s. The skin-electrode impedance was kept at <5 kΩ. During EEG recordings, subjects were asked to keep their eyes open and to fixate a point on the wall.

2.3. Data and statistical analysis

2.3.1. Subjective sleepiness

KSS scores were submitted to a two-way repeated measures analysis of variance (ANOVA) design: Day (Pre-SDEP vs Post-SDEP) × Time of Day (11:00 vs 23:00).

2.3.2. Psychomotor Vigilance Task

The following PVT variables were analyzed: median RTs, mean of the fastest 10% RTs (Fast RTs), mean of the slowest 10% RTs (Slow RTs). Premature response or RTs <100 ms were considered as false starts and thus excluded from analysis [9]. On each PVT variable, a two-way repeated measures ANOVA design, Day (Pre-SDEP vs Post-SDEP) × Time of Day (11:00 vs 23:00) was carried out.

Table 1
Means and standard errors of the PVT variables (median, fast and slow RTs), and relative main effects of Day (analysis of variance).

PVT	Day		$F(1, 15)$	P
	Pre-SDEP	Post-SDEP		
Median RT	132.8 ± 32.12	142.52 ± 2.78	12.16	0.003
Fast RT	109.77 ± 0.98	112.91 ± 1.47	8.09	0.01
Slow RT	210.67 ± 11.79	288.27 ± 30.25	6.66	0.02

PVT, psychomotor vigilance task; RTs, reaction times; SDEP, sleep deprivation.

2.3.3. Resting EEG

Ocular and muscle artefacts were offline-excluded by visual inspection of 2 s segments. Power spectra of the 19 EEG derivations were computed by a fast Fourier transform (FFT) routine in 2 s epochs across the delta (1–4 Hz), theta (5–7 Hz), alpha (8–12 Hz), beta 1 (13–15 Hz) and beta 2 (16–24 Hz) bands. Statistical comparisons for every EEG band and scalp location were carried out on log-transformed EEG power data by a two-way repeated measures ANOVA design, Day (Pre-SDEP vs Post-SDEP) × Time of Day (11:00 vs 23:00).

On the basis of the ANOVAs results, correlations between EEG, behavioral and self-rated sleepiness changes after SDEP were performed separately for each scalp location.

3. Results

3.1. Subjective sleepiness

After SDEP, subjects showed a high level of sleepiness, as indicated by a significant main increase in KSS scores (Pre-SDEP 4.37, SE ±0.46; Post-SDEP 7.12, SE ±0.40; $F(1, 15) = 26.69$; $P = 0.0001$). A significant main effect of Time of Day [$F(1, 15) = 6.75$; $P = 0.02$] was also observed, with higher KSS scores in the morning (11:00: 6.12, SE ±0.39; 23:00: 5.37, SE ±0.35), but it was characterized by a small effect size ($\eta^2 = 0.04$). The Day × Time of Day interaction was not significant [$F(1, 15) < 1$].

3.2. Psychomotor Vigilance Task

The main effects and interactions of the Day × Time of Day ANOVAs on all the PVT variables are reported in Tables 1–3. SDEP induced a clear deterioration of PVT performance (higher RTs), as denoted by a significant main effect of Day on median RTs, Fast RTs and Slow RTs. Only Slow RTs showed a significant effect of Time of Day, indicating longer reaction times in the morning compared with evening. No significant Day × Time of Day interactions were observed.

3.3. Resting EEG

Fig. 2 shows the topographic scalp maps of the main effects and interactions relative to the Day × Time of Day ANOVAs carried out on EEG power for the selected frequency bands. Results show significant main effects of Day, expressed by a post-SDEP increase in

Table 2
Means and standard errors of the PVT variables (median, fast and slow RTs), and relative main effects of Time of Day (analysis of variance).

PVT	Time of day		$F(1, 15)$	P
	Morning (11:00)	Evening (23:00)		
Median RT	138.90 ± 2.64	136.36 ± 2.06	1.12	0.31
Fast RT	111.75 ± 1.27	110.93 ± 1.27	0.47	0.5
Slow RT	280.90 ± 30.08	218.03 ± 10.10	4.89	0.04

PVT, psychomotor vigilance task; RTs, reaction times.

Table 3
Means and standard errors of the PVT variables (median, fast and slow RTs), and relative interactions of Day × Time of Day (analysis of variance).

PVT	Day × Time of Day				$F(1, 15)$	P
	Pre-SDEP		Post-SDEP			
	Morning	Evening	Morning	Evening		
Median RT	132.69 ± 2.58	132.97 ± 2.29	145.28 ± 4.07	139.75 ± 2.70	1.49	0.24
Fast RT	109.98 ± 1.13	109.56 ± 1.29	113.52 ± 1.72	112.30 ± 1.54	0.27	0.61
Slow RT	210.45 ± 11.22	210.88 ± 14.74	351.35 ± 58.35	225.18 ± 7.88	4.49	0.05

PVT, psychomotor vigilance task; RTs, reaction times; SDEP, sleep deprivation.

delta (C3, C4, Cz, F3, F4, F7, Fz, O1, O2, P3, P4, Pz, T3, T5), theta (every scalp location), alpha (Cz, F2, F3, F4, F8, Fz, T6) and beta 1 (C3, C4, Cz, F3, F4, F8, Fz, O2, P3, P4, Pz, T6) bands. Notably, no significant Time of Day effects or interactions were observed.

3.4. Correlations between EEG, behavioral and self-rated changes after sleep deprivation

The above results showed that both behavioral and subjective measures of sleepiness, as well as EEG power of delta, theta, alpha, and beta 1 band topography were influenced by SDEP (pre-SDEP vs post-SDEP comparisons), with only a main effect of Time of Day on the KSS measure (with a small effect size) and on the Slow RTs at PVT performance. Therefore, for each variable we used the difference between pre- and post-SDEP for the estimation of the possible associations between EEG, behavioral, and self-rated measures (i.e. collapsing values as a function of the time of day). Thus, EEG delta, theta, alpha, and beta 1 (all the bands in which a significant post-SDEP alteration has been observed) power of pre- and post-SDEP were averaged across the morning and the evening conditions, separately for each scalp location. Similarly, KSS and PVT measures were averaged through days 1 and 2. For each scalp location, Spearman's rank correlation coefficients were computed between EEG power changes (ΔDelta, ΔTheta, ΔAlpha and ΔBeta 1) and, respectively, post-SDEP changes of KSS (ΔKSS), PVT median RTs (ΔPVT median RTs), PVT Fast RTs (ΔPVT Fast RTs), and PVT Slow RTs (ΔPVT Slow RTs). To correct for multiple comparisons, the False Discovery Rate (FDR) was applied [24]. Namely, we controlled the proportion of type I errors among all the rejected null hypotheses by setting the FDR to a q-value of 0.05. The q-value is defined as the FDR analogue of the P-value. The q-value of an individual hypothesis test is the minimum FDR at which the test may be considered significant. The q-values were estimated through the procedure described by Storey et al. [24], running the software QVALUE (by Alan Dabney and John Storey). It is worth noting that the FDR estimate depends not only on the number of

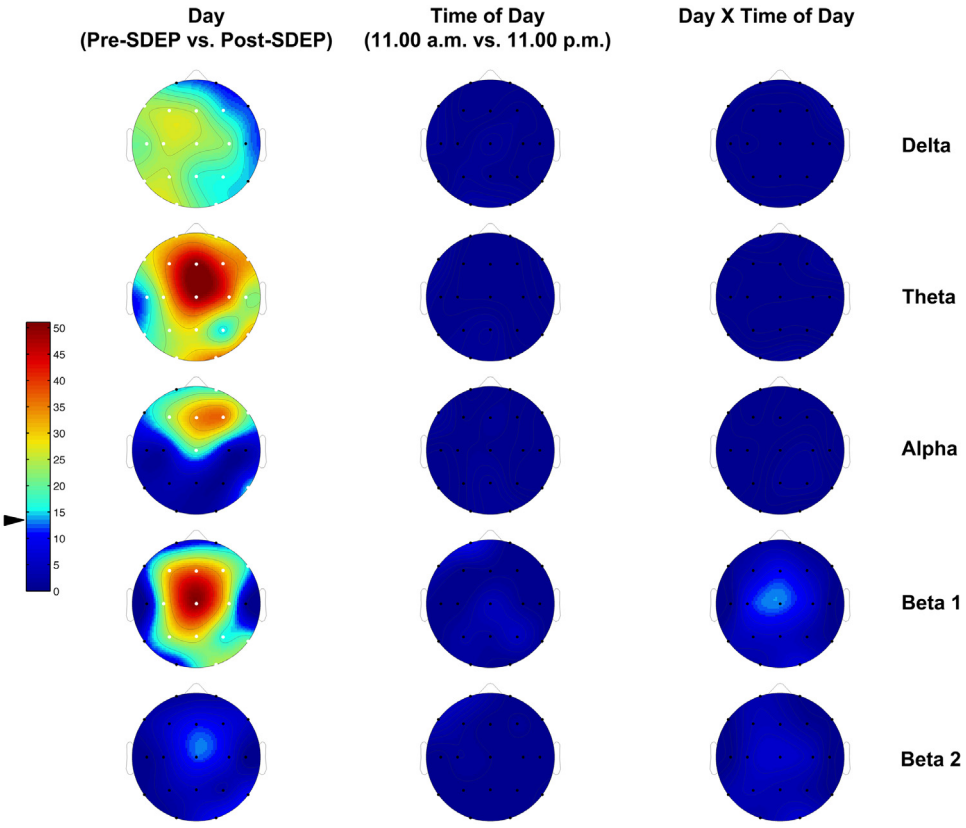

Fig. 2. Statistical maps of the main effects and interactions of the Day × Time of Day analyses of variance on electroencephalographic (EEG) delta, theta, alpha, beta 1 and beta 2 power in the eyes-open condition. Data are expressed as F-values ($n = 16$). The maps are based on the 19 unipolar EEG derivations of the 10–20 system (electrode positions indicated by dots) with averaged earlobe references (A1, A2). Values are color-coded and plotted at the corresponding position on the planar projection of the hemispheric scalp model. Values between electrodes were interpolated (biharmonic spline interpolation). Filled white circles indicate the electrodes with a significant difference (for the correction of multiple comparisons, see Results).

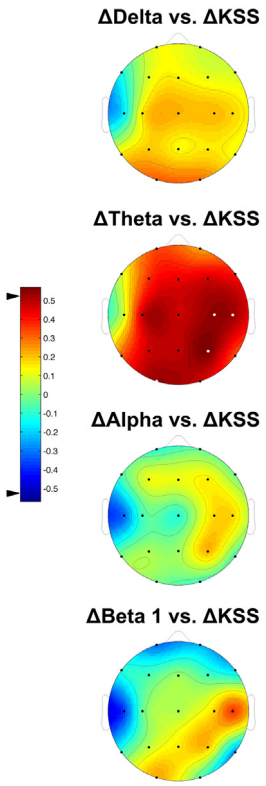

Fig. 3. Topographic distribution of the Spearman rank correlation coefficients ($n = 16$) between electroencephalographic (EEG) delta, theta, alpha and beta 1 power (ΔDelta, ΔTheta, ΔAlpha, ΔBeta 1, respectively) modifications after sleep deprivation (SDEP) and post-SDEP changes in Karolinska Sleepiness Scale (ΔKSS). Data are expressed as rho-values: positive rho-values indicate positive correlations and vice-versa. The maps are based on the 19 unipolar EEG derivations of the 10–20 system (electrode positions indicated by dots) with averaged earlobe references (A1, A2). Values are color-coded and plotted at the corresponding position on the planar projection of the hemispheric scalp model. Values between electrodes were interpolated (biharmonic spline interpolation). The level of significance after False Discovery Rate correction ($q \leq 0.04$; $P \leq 0.041$) corresponds to $\rho \geq 0.53$. Filled circles indicate the electrodes with a significant correlation.

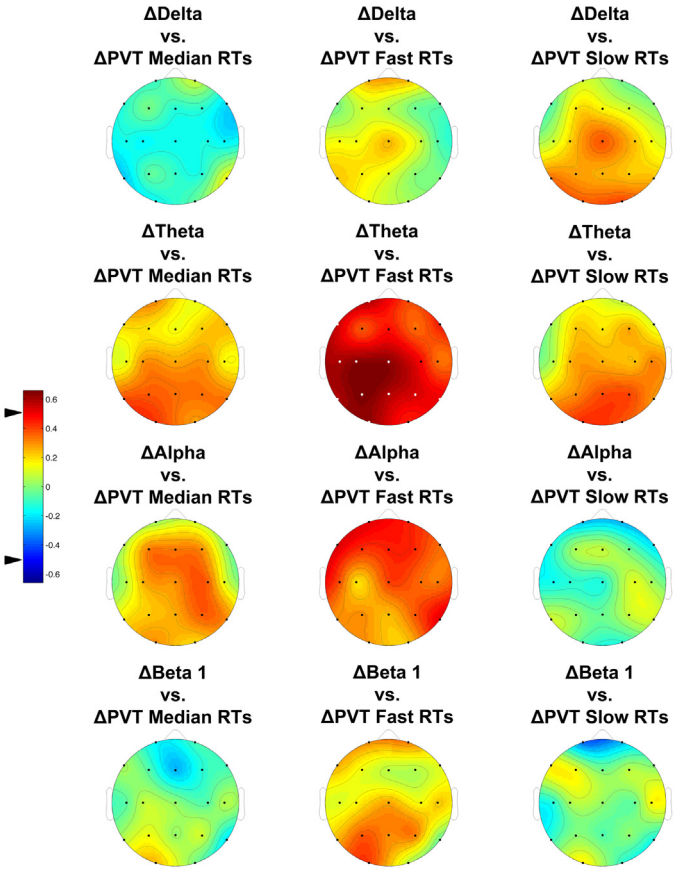

Fig. 4. Topographic distribution of the Spearman rank correlation coefficients ($n = 16$) between electroencephalographic (EEG) delta, theta, alpha and beta 1 power (ΔDelta, ΔTheta, ΔAlpha, ΔBeta1, respectively) modifications after sleep deprivation (SDEP) and post-SDEP changes in psychomotor vigilance task (PVT) measures [ΔPVT median reaction times (RTs), ΔPVT Fast RTs, ΔPVT Slow RTs, respectively]. Values are expressed in terms of rho-values: positive rho-values indicate the presence of positive correlations and vice-versa. The maps are based on the 19 unipolar EEG derivations of the 10–20 system (electrode positions indicated by dots) with averaged earlobe references (A1, A2). Values are color-coded and plotted at the corresponding position on the planar projection of the hemispheric scalp model. Values between electrodes were interpolated (biharmonic spline interpolation). The level of significance after False Discovery Rate correction ($q \leq 0.025$; $P \leq 0.048$) corresponds to $\rho \geq 0.51$. Filled circles indicate the electrodes with a significant correlation.

comparisons (as in the Bonferroni correction), but also on the specific *P*-values.

The topographic distribution of the correlation coefficients between post-SDEP changes in EEG power and KSS (Fig. 3) shows significant positive correlations (FDR $q \leq 0.04$; $P \leq 0.041$ corresponds to $\rho \geq 0.53$) between ΔTheta and ΔKSS at C4, O1, P4 and T4 scalp locations. Fig. 4 shows the topographic distribution of the correlation coefficients between each PVT variable and, ΔDelta, ΔTheta, ΔAlpha and ΔBeta 1, respectively, showing significant positive correlations (FDR $q \leq 0.025$; $P \leq 0.048$ corresponds to $\rho \geq 0.51$) between ΔTheta and ΔPVT Fast RTs at C3, Cz, F1, F7, P3, P4, Pz, O1, T3, T5, and T6 scalp locations. Since ANOVA results showed a main effect of Time of Day on the PVT Slow RTs, the Speraman rank correlation coefficients between ΔPVT Slow RTs and, respectively, ΔDelta, ΔTheta, ΔAlpha and ΔBeta 1 were also calculated separately for the difference between morning sessions (3 vs 1) and evening sessions (4 vs 2), showing no significant correlation (Fig. 5).

Finally, the correlations between ΔKSS and all the PVT measures (ΔPVT median RTs, ΔPVT Fast RTs, and ΔPVT Slow RTs) point to a significant positive association between ΔKSS and ΔPVT Fast RTs ($\rho \geq 0.60$; $P \leq 0.02$), between ΔKSS and ΔPVT Slow RTs ($\rho \geq 0.50$; $P = 0.05$), and a weaker association between ΔKSS and ΔPVT median RTs ($\rho \geq 0.41$; $P \leq 0.12$) (Fig. 6).

4. Discussion

To the best of our knowledge, this is the first study aimed at assessing the relationship between PVT performance and EEG scalp topography during prolonged wakefulness. According to our hypotheses, SDEP induced a global increase in delta and theta activity (and an increase in alpha and beta 1 EEG activity in specific scalp locations), higher levels of subjective sleepiness and, a slowing of RTs at the PVT (in terms of median RTs, Fast RTs and Slow RTs). Both KSS scores and PVT measures (Fast RTs) were positively correlated with the post-SDEP theta increase, particularly in centro-posterior regions. Significant positive relations were also observed between subjective sleepiness ratings and behavioral performance at the PVT.

4.1. The relationship between EEG, behavioral, and subjective measures of sleepiness

The most original finding is the positive correlation observed between PVT performance (mainly, Fast RTs) and EEG topography in specific scalp locations. The positive correlation between Fast RTs

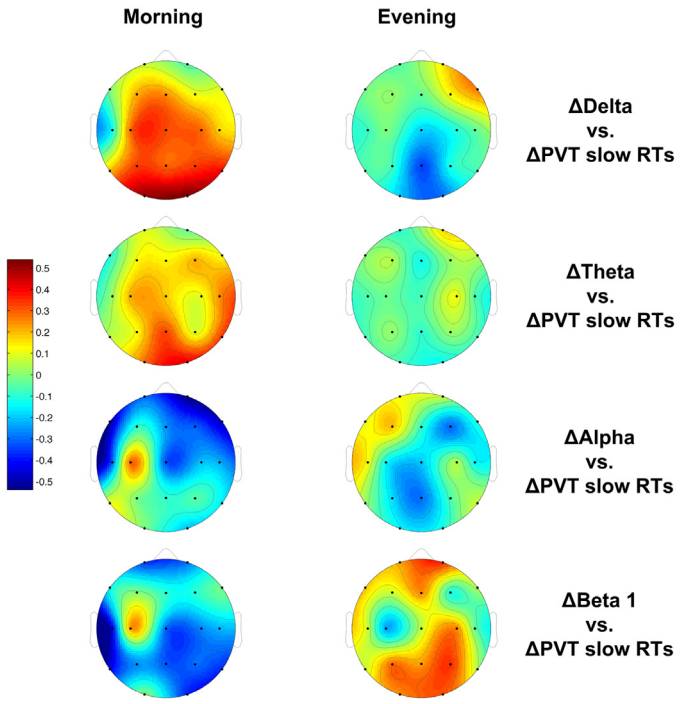

Fig. 5. Topographic distribution of the Spearman rank correlation coefficients ($n = 16$) between electroencephalographic (EEG) delta, theta, alpha and beta 1 power (ΔDelta, ΔTheta, ΔAlpha and ΔBeta 1, respectively) modifications after sleep deprivation (SDEP) and post-SDEP changes in psychomotor vigilance task (PVT) slow reaction times (ΔPVT Slow RTs), separately for the morning and the evening sessions. Values are expressed in terms of rho-values: positive rho-values indicate positive correlations and vice-versa. The maps are based on the 19 unipolar EEG derivations of the 10–20 system (electrode positions indicated by dots) with averaged earlobe references (A1, A2). Values are color-coded and plotted at the corresponding position on the planar projection of the hemispheric scalp model. Values between electrodes were interpolated (biharmonic spline interpolation).

and EEG topography is frequency specific, involving only theta activity, not the other frequency bands. Albeit the positive correlation between Fast RTs and theta activity observed in all cortical derivations, significance was reached only in a circumscribed area involving the left central, parietal, temporal, and occipital lobes in a couple of left frontal derivations and in the right temporal and parietal areas. This finding is partially coherent with the positive correlation between an increase in RTs and absolute EEG power (4–20 Hz) reported in a visual discriminative task after SDEP [14].

Behavioral data indicate that SDEP affects the PVT measures differently, suggesting that different neurophysiological mechanisms may underlie changes in different PVT variables after SDEP. Fast RTs at the PVT in well-rested subjects are associated with increased blood-oxygen-level dependent (BOLD) activity in the fronto-parietal sustained-attention network and in cortical and subcortical motor systems, whereas Slow RTs were correlated with the activation of the "default mode" brain network, more markedly after total SDEP [12]. The positive correlations in this study between EEG and Fast RTs have clear centro-posterior maxima, and only partially overlap results obtained by fMRI measures [12]. It should, however, be remembered that in our study the EEG was recorded before the beginning of the PVT trials, whereas Drummond et al. [12] collected fMRI data during the execution of the PVT. Hence, it is likely that differences may be ascribed to specific networks implicated in the execution of the task. In a similar manner, alternating periods of EEG recordings and periods of task engagement during 24 h of prolonged wakefulness are associated with two different patterns of regional increase of theta power [25], as a function of two different kinds of task: a left frontal focus for a language task and a parietal posterior focus for a visuo-motor task.

A small circadian influence seems to affect only Slow RTs. Albeit not significant, the scalp topography of correlations gives some cues about the EEG basis of the Slow RTs. Fig. 5 indicates that, in the morning, post-SDEP changes in Slow RTs show positive (not significant) correlations with EEG power modification in a wide centro-posterior area for the delta band and in occipital and left temporal regions for the theta band, whereas close-to-significant negative correlations can be observed for alpha (in left frontal and right temporal areas) and beta 1 (in the left temporal region) bands. Conversely, in the evening, a negative correlation between delta frequency and Slow RTs can be observed in centro-posterior regions, whereas beta 1 shows positive correlation in frontal and centro-posterior areas. Future studies should be addressed to better understand the neurophysiological mechanisms underlying the Slow RTs.

Finally, the significant positive correlations between KSS and theta EEG involve centro-posterior areas, partially overlapping the scalp topography of the significant correlations between Fast RTs and theta

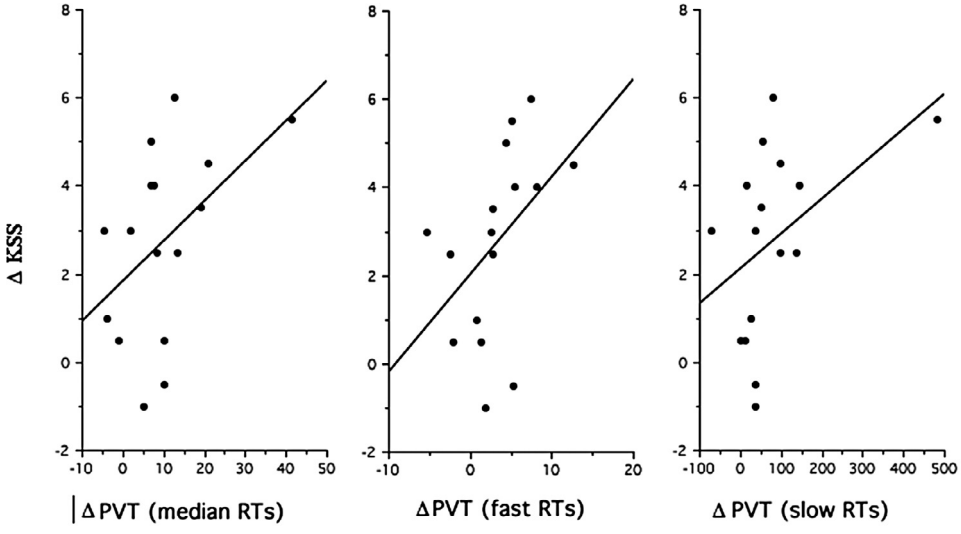

Fig. 6. Scatterplots of the individual correlations between post-sleep deprivation (SDEP) changes in Karolinska Sleepiness Scale (ΔKSS) and modifications after SDEP of the psychomotor vigilance task (PVT) measures: ΔPVT median reaction times (RTs) ($\rho \geq 0.41$), ΔPVT Fast RTs ($\rho \geq 0.60$) and ΔPVT Slow RTs ($\rho \geq 0.51$), respectively.

activity, even if with a different lateralization (more right-oriented for the correlation between KSS and theta). This result is corroborated by the observation of a significant positive correlation between KSS and Fast RTs. The association between high level of subjective sleepiness measured with KSS and increased EEG theta power after SDEP is well supported by the evidence [23,26]. At a topographical level, Strijkstra et al. [27] found a general positive correlation between theta activity and KSS results, but with fronto-central maxima. Their topographical distribution may be due to the fact that in the Strijkstra et al. study [27] subjects had their eyes closed during the EEG recordings, whereas our subjects had eyes opened, staring at a point on the wall. Probably, this condition engages more resources from posterior visuo-attentional areas than an eyes-closed condition.

Together, our findings suggest that similar neurophysiological mechanisms may reduce both increased subjective sleepiness and slowed Fast RTs after sleep loss. In general, these results strengthen the view that sleep need is locally expressed [18]. In view of a behavioral and/or subjective assessment of daytime sleepiness, our results suggest that PVT and KSS may be more accurate predictors of worsened perceptual as compared with executive functions.

4.2. PVT performance

Results confirm the PVT sensitivity to sleep disruption [8–11], showing that all the considered PVT measures were negatively affected by SDEP. The only variable influenced by circadian factors was the Slow RT, pointing to a worse performance in the morning. Albeit some studies showed that the overall PVT performance undergoes circadian modulation [28,29], our results indicate that lapses and Slow RTs are the PVT variables most sensitive to the circadian drive (see also [30]). Coherently, during a forced desynchronization protocol only the PVT lapses and Slow RTs (not the median and the Fast RTs) were associated with changes in body temperature, with better performance when body temperature was higher [31]. Together, these results suggest that sleepiness may differently affect PVT outcome variables: whereas a clear homeostatic factor influences all the PVT measures, a circadian modulation seems to affect mainly (or exclusively) the Slow RTs. A possible explanation for the incoherence between our results and those showing a general circadian influence on PVT performance may originate from the data collection protocol: whereas in our study measures were collected only at 11:00 and 23:00 on the first and second day, in other studies subjects performed the PVT at different times of day. Thus, our protocol might be not sufficiently sensitive to the circadian changes. However, this question goes beyond the aim of the present study, since we were mainly interested in the EEG topographic correlates of the PVT performance after SDEP, just 'controlling' for the presence of a circadian modulation.

4.3. EEG scalp topography

A significant increase in the EEG power after SDEP has been observed for every frequency band with the notable exception of beta-2, in line with previous findings showing a post-SDEP increase in the ranges 0.75–9 Hz and 11–16.5 Hz [19–21]. Theta frequency increased significantly in all cortical areas with time elapsed awake, confirming its role as a sensitive EEG index of sleepiness [19–21]. According to previous findings, theta activity after SDEP was more prominent in fronto-central regions [19], underlying these areas' higher recovery need [32–34], and (secondary) in occipital regions [19]. The delta band shows a generalized increase after SDEP, coherently with results from previous works [19–21]. The significant rise of alpha and beta 1 in specific sites mostly overlaps the only available studies [19,21]. With respect to the beta 1 band, its increase after SDEP has been frequently observed [15,20,35], and it has been interpreted usually in terms of emerging spindle activity during wake.

The lack of time-of-day effect on any frequency band suggests that the EEG cortical topography during SDEP is more affected by homeostatic than by circadian influences. The prevalence of a homeostatic factor on theta activity compared with the circadian factor has been previously observed [15,36], whereas the absence of circadian influence on the other bands is more controversial. In a previous study, an influence of circadian factor on every frequency band was found [36]. This difference may be due to a methodological bias, since Marzano et al. [36] recorded the EEG every hour across a 40 h SDEP protocol with a 36-data-point resolution.

Finally, a limitation of the current study is represented by the long periods without EEG monitoring between the four recording sessions: albeit subjects were always strictly controlled by at least one experimenter, short episodes of light sleep during these periods cannot be excluded, particularly during periods of low attentional demand.

5. Conclusion

The present findings supply the first evidence of an association between the EEG low-frequency topographical distribution and PVT performance after SDEP, showing a positive frequency-specific correlation between Fast RTs and the increased theta activity, particularly in centro-posterior areas. This topographic distribution of correlations partially overlaps the scalp map of the relationship between self-rated sleepiness and theta activity. Moreover, PVT measures and self-rated sleepiness were positively correlated. Together, these findings suggest that the deterioration of performance at the PVT and the increase in subjective sleepiness may share a similar pattern of cortical activation after SDEP, strengthening the view that sleep need is also locally expressed.

According to current results, assessment of daytime sleepiness behaviorally and/or subjectively should take into account that PVT and KSS may be more accurate predictors of worsened perceptual compared with executive functions.

Finally, our results strengthen the validity of the PVT as a useful tool for the assessment of the behavioral effect of sleep loss, although it appears that Slow and Fast RTs may be differently affected by circadian factors.

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Conflict of interest

None declared.

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References

[1] Dinges DF. An overview of sleepiness and accidents. J Sleep Res 1995;4(Suppl. 2):4–14.
[2] Horne JA, Reyner LA. Driver sleepiness. J Sleep Res 1995;4(Suppl. 2):23–9.
[3] Shen J, Barbera J, Shapiro CM. Distinguishing sleepiness and fatigue: focus on definition and measurement. Sleep Med Rev 2006;10:63–76.
[4] Dinges DF, Kribbs NB. Performing while sleepy: effects of experimentally-induced sleepiness. In: Monk TH, editor. Sleep, sleepiness and performance. Chichester: Wiley; 1991. p. 97–128.

[5] Jones K, Harrison Y. Frontal lobe function, sleep loss and fragmented sleep. Sleep Med Rev 2001;5:463–75.
[6] Dinges DF, Powell JW. Microcomputer analyses of performance on a portable, simple visual RT during sustained operations. Behav Res Methods Instrum Comput 1985;17:652–5.
[7] Lim J, Dinges DF. Sleep deprivation and vigilant attention. Ann N Y Acad Sci 1995;1129:305–22.
[8] Jewett ME, Dijk DJ, Kronauer RE, Dinges DF. Dose–response relationship between sleep duration and human psychomotor vigilance and subjective alertness. Sleep 1999;22:171–9.
[9] Doran SM, Van Dongen HPA, Dinges DF. Sustained attention performance during sleep deprivation: evidence of state instability. Arch Ital Biol 2001;139:253–67.
[10] Van Dongen HP, Dinges DF. Investigating the interaction between the homeostatic and circadian processes of sleep–wake regulation for the prediction of waking neurobehavioral performance. J Sleep Res 2003;12:181–7.
[11] Van Dongen HP, Maislin G, Mullington JM, Dinges DF. The cumulative cost of additional wakefulness: dose–response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. Sleep 2003;26:117–26.
[12] Drummond SPA, Bischoff-Grethe A, Dinges DF, Ayalon L, Mednick SC, Meloy J. The neural basis of the psychomotor vigilance task. Sleep 2005;28: 1059–68.
[13] Raichle ME, MacLeod AM, Snyder AZ, Powers WJ, Gusnard DA, Shulman GL. A default mode of brain function. Proc Natl Acad Sci U S A 2001;989:676–82.
[14] Corsi-Cabrera M, Arce C, Ramos J, Lorenzo I, Guevara MA. Time course of reaction time and EEG while performing a vigilance task during total sleep deprivation. Sleep 1996;19:563–9.
[15] Cajochen C, Khalsa SBS, Wyatt JK, Czeisler CA, Dijk DJ. EEG and ocular correlates of circadian melatonin phase and human performance decrements during sleep loss. Am J Physiol Regul Integr Comp Physiol 1999;277:R640–9.
[16] Hoedlmoser K, Griessenberger H, Fellinger R, Freunberger R, Klimesch W, Gruber W, et al. Event-related activity and phase locking during a psychomotor vigilance task over the course of sleep deprivation. J Sleep Res 2011;20:377–85.
[17] Caldwell JA, Prazinko B, Caldwell JL. Body posture affects electroencephalographic activity and psychomotor vigilance task performance in sleep-deprived subjects. Clin Neurophysiol 2003;114:23–31.
[18] Ferrara M, De Gennaro L. Going local: insights from EEG and stereo-EEG studies of the human sleep–wake cycle. Curr Top Med Chem 2011;11:2423–37.
[19] De Gennaro L, Marzano C, Veniero D, Moroni F, Fratello F, Curcio G, et al. Neurophysiological correlates of sleepiness: a combined TMS and EEG study. Neuroimage 2007;33:1277–87.
[20] Finelli LA, Baumann H, Borbély AA, Achermann P. Dual electroencephalogram markers of human sleep homeostasis: correlation between theta activity in waking and slow-wave activity in sleep. Neuroscience 2000;101: 523–9.
[21] Tinguely G, Finelli LA, Landolt HP, Borbély AA, Achermann P. Functional EEG topography in sleep and waking: state-dependent and state-independent features. Neuroimage 2006;32:283–92.
[22] Curcio G, Tempesta D, Scarlata S, Marzano C, Moroni F, Rossini PM, et al. Validity of the Italian version of the Pittsburgh Sleep Quality Index (PSQI). Neurol Sci 2013;34:511–19.
[23] Åkerstedt T, Gillberg M. Subjective and objective sleepiness in the active individual. Int J Neurosci 1990;52:29–37.
[24] Storey JD, Taylor JE, Siegmund D. Strong control, conservative point estimation, and simultaneous conservative consistency of false discovery rates: a unified approach. J R Stat Soc Series B Stat Methodol 2004;66:187–205.
[25] Hung CS, Sarasso S, Ferrarelli F, Rieder B, Ghilardi MF, Cirelli C, et al. Local experience-dependent changes in the wake EEG after prolonged wakefulness. Sleep 2013;36:59–72.
[26] Horne JA, Baulk SD. Awareness of sleeping when driving. Psychophysiology 2004;41:161–5.
[27] Strijkstra AM, Beersma DGM, Drayer B, Halbesma N, Daan S. Subjective sleepiness correlates negatively with global alpha (8–12 Hz) and positively with central frontal theta (4–8 Hz) frequencies in the human resting awake electroencephalogram. Neurosci Lett 2003;340:17–20.
[28] Van Dongen HP, Dinges DF. Circadian rhythm in sleepiness, alertness and performance. In: Kryger MH, Roth T, Dement WC, editors. Principles and practice of sleep medicine. Philadelphia, PA: Saunders; 2000. p. 435–43.
[29] Wyatt JK, Ritz-De Cecco A, Czeisler CA, Dijk DJ. Circadian temperature and melatonin rhythms, sleep, and neurobehavioral function in humans living on a 20-h day. Am J Physiol 1999;277(4 Pt 2):R1152–63.
[30] Graw P, Kräuchi K, Knoblauch V, Wirz-Justice A, Cajochen C. Circadian and wake-dependent modulation of fastest and slowest reaction times during the psychomotor vigilance task. Physiol Behav 2004;80:695–701.
[31] Wright KP Jr, Hull JT, Czeisler CA. Relationship between alertness, performance, and body temperature in humans. Am J Physiol Regul Integr Comp Physiol 2002;283:R1370–7.
[32] Horne JA. Human sleep, sleep loss and behaviour. Implications for the prefrontal cortex and psychiatric disorder. Br J Psychiatry 1993;162:413–19.
[33] Finelli LA, Borbély AA, Achermann P. Functional topography of the human nonREM sleep electroencephalogram. Eur J Neurosci 2001;13:2282–90.
[34] Mander BA, Reid KJ, Baron KG, Tjoa T, Parrish TB, Paller KA, et al. EEG measures index neural and cognitive recovery from sleep deprivation. J Neurosci 2010;30:2686–93.
[35] Aeschbach D, Matthews JR, Postolache TT, Jackson MA, Giesen HA, Wehr TA. Dynamics of the human EEG during prolonged wakefulness: evidence for frequency-specific circadian and homeostatic influences. Neurosci Lett 1997;239:121–4.
[36] Marzano C, Fratello F, Moroni F, Pellicciari MC, Curcio G, Ferrara M, et al. Slow eye movements and subjective estimates of sleepiness predict EEG power changes during sleep deprivation. Sleep 2007;30:610–16.